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STUDIES ON SOIL STRUCTURE: EFFECT OF PUDDLED SOILS ON PLANT GROWTH

By

W. T. McGeorge and J. F. Breazeale

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‡In co-operation with United States Department of Agriculture, Bureau of Agricultural Engineering.

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STUDIES ON SOIL STRUCTURE: EFFECT OF PUDDLED SOILS ON PLANT GROWTH

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INTRODUCTION

This is the fourth of a series of bulletins dealing directly with the physical aspects of our productivity problems and concerns the soil-plant relationships. The previous bulletins have dealt with gas movement in soils (9), the physical characters of puddled soils (22), and the effect of puddled soils on nitrogen transformations (8). In the southwestern part of the United States soil conservation is a much broader problem than in many other sections. On the range lands and in some other areas which are not under cultivation there is a distinct and serious problem in erosion loss. On the irrigated lands soil conservation is largely a problem involving a deterioration in soil structure and methods of structural preservation. This structural deterioration commonly accompanies the bringing of arid lands under cultivation and irrigation and is usually manifested by a progressive loss in the productivity of the soil. Irrigation waters of desirable quality are not always available, and this together with certain cultural practices and the nature of the bases which are combined with the exchange complex (the clay fraction) contributes to a comparatively rapid rate of structural deterioration on some soil types.

In view of the above, soil productivity studies on the irrigated lands of Arizona demand that considerable stress be placed on physical problems. In fact in many cases structural characteristics are the principal growth-limiting factors. While texture is of great importance also, it is by no means the controlling factor in as many cases as structure. To be in good physical condition a soil should be loose, friable, possess a so-called crumb structure, work well, and have what is referred to by some as a "live appearance." These are all characters which are easy to recognize but not susceptible to exact measurement or quantitative expression.

This problem of soil conservation or, to use a better term, productivity conservation demands either a soil program designed to retard or prevent the process of structural deterioration or an occasional treatment to reverse the process by reclaiming or rebuilding the soil structure. The latter may be accomplished by the use of such soil amendments as gypsum, sulphur, manure, a dry fallow, or some combination of these.

Structural breakdown is most often attributed to careless tillage. Soil structure will be seriously disturbed when a soil that is within a certain range of moisture content which reaches its maximum at the moisture equivalent is subjected to some type of mechanical disturbance. Within this range of moisture content the soil particles tend to arrange themselves into a compact mass of impermeable material.

While careless tillage is a common cause, an irrigation practice which is unsuited to the soil type may often be a serious contributing factor under the most careful tillage program. This is especially true if only soft waters are available for irrigation and the base exchange complex contains too large a content of sodium. In order for a soil to maintain a desirable structure under irrigation its aggregates must be water stable otherwise there will be a rapid loss in structure. The principal object in preserving a good soil structure is to maintain a minimum restriction to the movement of air and water within the soil. The best irrigation program is one which involves the most effective balance between too much water and too little air. All soils even in their virgin state possess a certain degree of permeability which is usually referred to as the ability to "take water." Under the combined influence of irrigation and cultivation it is within our power to reduce or improve this property. Structural breakdown from irrigation can often be traced to soil crumbs of such a composition as to render them unstable when wet. These soils are either readily dispersed or puddled and as such may contribute to a compactly massed character or a migration of colloidal particles to lower soil horizons to form compact subsoil layers.

An illustration of water instability as applied to Egyptian soils is given by Greene and Snow (16).

> When dry the soil of the Gezira is deeply cracked, the surface consisting of moderately hard lumps, together with a loose mulch of smaller particles. When moistened the desiccated lumps break down into a friable soil having an attractive loamy texture, which gives place to an increasingly clay like consistency with continued watering. After a period of dry fallow the soil returns apparently to its original condition.

It is evident from this description that some Egyptian soils undergo rather rapid structural deterioration when irrigated and that while a dry fallow improves the soil structure the aggregates are not water stable. It is with the idea of establishing water stability that we usually recommend the use of gypsum with a dry fallow. The calcium in the gypsum, when absorbed by the clay and colloid particles, has the property of building water-stable crumbs. It is said that in some sections of the Nile Valley structural deterioration is so rapid that one year's cropping (cultivation and irrigation) will destroy the benefit of ten years' dry fallow. While this is probably an extreme case it well illustrates the magnitude of structural breakdown in some soils under irrigation.

Under field conditions a soil is composed of particles varying in size from a pinhead or smaller to an inch or more in diameter. These lumps are easily broken down on grinding and if mixed with water may separate into particles many of which are too small to be seen by the naked eye. These minute particles contribute more to soil structure than any other factor, either as migratory particles, as a cementing agent in the particle clusters which we call crumbs, or in other ways.

A previous bulletin from this laboratory (22) has shown something of the structural behavior of soils when the aggregates are destroyed by working at the critical and other moisture contents to produce different degrees of puddling. In this bulletin the differentiation between soil puddling and soil dispersion and soil structure and soil texture is stressed. Since we are interested in soils largely because of their function in crop production, physical properties must ultimately be considered in relation to plant growth. This relation between soil structure and plant growth may be expressed as soil tilth. Our investigations show that our major interest should be in the physical character which we have designated as the puddled state. Heavy, refractory soils have a high moisture capacity, but water is not easily usable by plants unless the structure is favorable to aeration and root penetration.

The quantitative measure of soil texture is a relatively simple task, while that of soil structure is highly complicated. The reason for this is that we are not sufficiently acquainted with the numerous physical phenomena which are associated with changes in soil structure. Investigations now in progress in this laboratory indicate that the values which we have termed the puddling ratio or degree of puddling may be of some use (22). These values are simply comparisons between the maximum percentage of suspended solids in a soil suspension after one hour's standing and the suspended solids as determined on the soil direct from the field and after air drying.

The degree of puddling is a function of the moisture content of the soil at the time it is plowed, cultivated, or otherwise disturbed. While maximum puddling or compaction occurs at the moisture equivalent, lesser compaction will take place within a certain range both above and below this point. Bradfield (7) has recently stated with reference to soil compaction "in many cases from 25 to 30 percent more soil is crammed into a cubic foot than was present in the virgin soil." Since this reference is made to soils in general, one can readily visualize how much more serious the problem of compaction or puddling may become in the irrigated soils of arid regions which contain practically no organic matter and proportionately large amounts of replaceable sodium. When a soil contains an excess of water, that is an amount represented by the water-holding capacity or higher, the moisture films are quite thick, and the soil particles are free to be moved with a minimum of friction, and hence there is little puddling in this moisture range. Such a soil is said to be well lubricated. At moisture contents approximating the moisture equivalent the moisture films are thinner, and considerable friction is developed when the soil is kneaded or worked. This is the range of maximum puddling. Under such conditions the soil assumes a puddled or plastic state when cultivated. At certain minimum moisture contents the soils are held apart partly by air films, and their structure is actually improved by cultivation. It is obvious that under the first and last conditions little or no puddling will result regardless of how greatly the soil is disturbed. Cameron and

Gallagher (11) also found that the moisture equivalent represents the moisture content at which a number of maximum and minimum physical values were obtained.

As a medium for the growth of plants it is imperative that the soil structure be such as to permit the free movement of air and water. The growth of plants in water cultures may be cited as an illustration of the effect of soil structure on plant growth, for in such cultures a more vigorous growth and greater absorption of ions will take place if the culture solution is aerated. It is also common knowledge that plants develop more extensive root systems in sandy soils than in clay soils. Reactions taking place within the root-soil contact film are in the main oxidizing reactions and therefore require a ready supply of oxygen. Also the soil structure must be of sufficient porosity to allow complete diffusion of the carbon dioxide given off by the roots in the oxygen-carbon dioxide exchange, otherwise the roots, which exist wholly below the surface of the soil, will cease to support the above-ground part of the plant, and some type of physiological distress will be manifested. The mere presence of ample available plant food in the soil cannot assure optimum plant growth. There must be free movement of both air and water.

There are so many factors and abnormal conditions associated with the soil structure known as the puddled state that a study of plant behavior in puddled soils involves many difficulties. The effects of puddling are manifested by very definite changes in the physical, chemical, and biological properties of both the solid and liquid phases of the soil. The plant may show a moisture stress in the presence of a high percentage of water in the soil. It may show a plant-food stress even though the soil is well fertilized. The air stress is the only one which exists in puddled soils as an actual deficiency.

The literature on the husbandry of waterlogged soils is quite extensive but little of this deals specifically with puddled soils. For an excellent review of the literature on cultivation the reader is referred to Sewell (25). While the value of cultivation is a decidedly controversial subject, the practice undoubtedly promotes oxidation, improves the availability of plant food, stimulates bacterial action and has other desirable properties when properly employed. This is well illustrated by the comparative fertility of surface soils and subsoils and the crop injury which usually follows deep plowing if the subsoil is turned over. The debatable points probably involve the practice of cultivation during the growth of the crop. At this period, when weeds must be controlled and moisture conserved, the greatest danger of puddling exists.

EXPERIMENTAL

Under field conditions such as exist in irrigated soils it is difficult to conduct field experiments in soil puddling in a manner which will assure accurate control of the degree of puddling one desires to study. This is due to the wide fluctuations in temperature and soil moisture in the Southwest. In view of this most of our experimental work has been confined to the laboratory and greenhouse. Much of the work was conducted by employing a modification of the Neubauer test (26). In this test 100 rye seeds were planted in 100 grams of soil and covered with a surface layer of sand to assure good germination of seed and to permit good aeration during growth. The seed was always planted between two layers of sand which were placed above the soil. By changing the physical structure of the soil used in the test it is possible to affect the growth of the plants measurably.

It was not the intent of these tests to determine actual Neubauer values. Since the Neubauer values are relative they must all be determined under carefully controlled and reproducible conditions in order to be comparable with one another. We were interested primarily in the relative absorption by the plants from the differently treated soils in each individual series. The separate series were not all grown for the same length of time, and so instead of Neubauer values the quantitative data on plant-food absorption are given in total milligrams absorbed by the culture of 100 plants. This will explain slight variations in the data obtained in the several different series.

Effect of Puddling on Seed Germination

If the seeds of any common crop are planted in a puddled soil and if the soil is kept thoroughly puddled and no cracks are allowed to form there will usually be no germination. However, if a crack forms, or other means are provided for air to enter the soil, some germination will take place. Soil structure therefore has a great influence on seed germination as well as plant growth.

In Plate I three pots of tomato plants are shown which were started from seed. An equal number of seeds were planted in each pot. The pot on the left was untreated and therefore acted as a control. The soil in the center pot was thoroughly puddled, while the pot on the right contains soil which was unpuddled, but air was excluded from the seeds by rolling them in a thick gum before planting. It will be noted that the untreated soil gave a high percentage germination and the plants were making excellent growth at the time the photograph was taken. The seeds in the puddled soil germinated only around the edge of the pot where cracks had developed and air was available. The seeds that had been rubbed into the gum failed to germinate just as did those in the puddled soils. The exceptions were seeds which were not completely embedded in the gum.

This simple experiment illustrates the effect of soil puddling on seed germination as well as early plant growth—that is, when the soil is in a maximum state of puddling and is maintained as such. Since there are many degrees of puddling, and therefore puddling is a relative term, it seems fair to assume that soil productivity will be influenced in relative degrees by the magnitude of the

Plate I.—The effect of puddled soil on seed germination: left, control; middle, puddled soil; right, seed rolled in thick gum before planting.

structural deterioration. Furthermore the puddled condition may exist only in the surface layer of soil, in one or more subsoil horizons, or as a highly dispersed or puddled condition existing throughout the root zone.

This experiment also illustrates the difficulties involved in attempting to make puddling studies under field conditions. In our preliminary field experiments we have observed that the excessive aridity of the climate dries the surface layer quite rapidly, cracks develop, layers of soil about 1 inch in thickness break off and these will dry sufficiently to partially rebuild the structure of this layer during the period between irrigations. Plentiful germination takes place in these cracks and they soon harbor active root growth. Under such conditions wide variations between the foraging habits of surface-feeding plants and deep-rooting plants will greatly alter results and conclusions. For example, here in Arizona we have obtained evidence that lettuce will make a remarkably good growth in some puddled soils when heavily fertilized. On the other hand, cotton which is a deep-rooting plant may show considerable stress in the nature of retarded development during the hot weather if the soil is in a puddled condition.

Effect of Dust Mulch on Plant Growth in a Puddled Soil

It is common observation to find soil under sod in good physical condition, and this has been attributed, at least in part, to the myriads of fibrous roots which the grass sends throughout the soil. In view of the fact that straw and paper mulches also improve the soil structure it is probable that the sod also has a mulching effect. In this connection it has been observed here in Arizona that the structure of a puddled soil may be greatly improved by a dust mulch if the dust is applied to the wet, puddled soil and the whole allowed to dry. This observation was first made by E. S. Turville, at that time Extension Agronomist, and was demonstrated under field conditions. The demonstration was conducted by puddling small plots of ground. While still wet they were leveled down and covered with a dust mulch. Other plots were puddled in a similar manner but were not mulched. After an interval of several weeks an examination of these plots showed that the unmulched puddled soil had dried to a hard refractive mass, while the soil under the dust mulch was porous and of good structure.

Our previous studies have shown that the dust mulch stimulates active nitrification in a puddled soil (8) in addition to converting the puddled soil into a more friable condition (22).

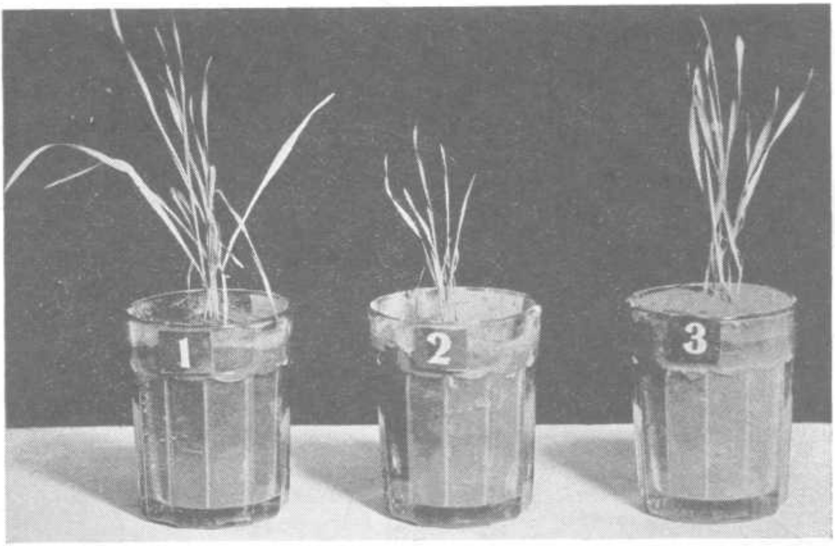

Plate II.—The effect of dust mulch on growth of barley seedlings: *1*, control; *2*, puddled soil; *3*, puddled soil mulched with dry dust.

The next experiment was therefore designed to determine the properties and effect of the dust mulch as indicated by plant growth. Three glass tumblers were filled with soil and sufficient water added to bring the moisture content to a point slightly below saturation. They were then planted with barley seedlings which were five days old. Tumblers *2* and *3* (Pl. II) were then puddled with an electric vibrator. This method of puddling the soil does not puddle it as thoroughly as working with a spatula but is sufficiently effective to illustrate the results desired. It is conducted by placing the off-center head of an electric vibrator (Pl. V) against the vessel containing the soil. The effect on structure can be observed immediately. When the soils were completely puddled, that in *3* was covered with a dust mulch of about ½ inch depth, and *2* was left with the surface exposed. At the end of five days the plants were photographed (Pl. II).

Another experiment was conducted in which transplanted tomato seedlings were used and larger pots of soil employed. In Plate III, *1*, the soil was thoroughly puddled and left with the surface exposed. In *2* the surface of the puddled soil was covered with a dust mulch and was mulched on the sides and bottom by a larger pot filled with dry soil. Both soils were equally puddled

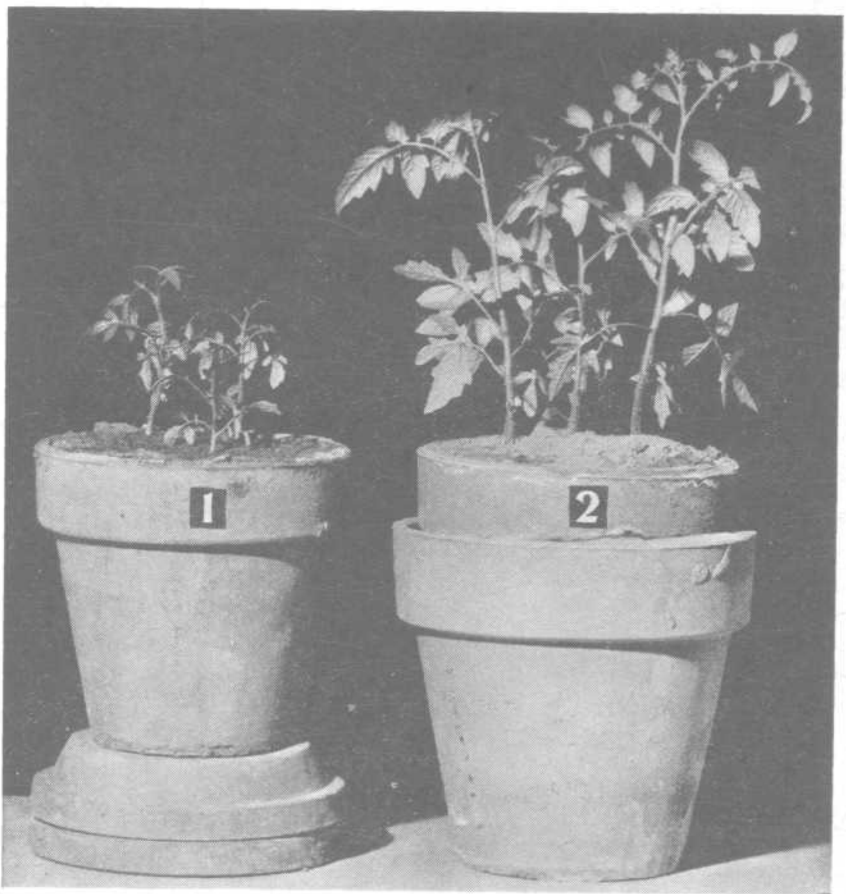

Plate III.—The effect of dust mulch on growth of tomato plants: *1*, puddled soil; *2*, puddled soil mulched with dry dust.

at the start of the experiment and kept at the same moisture content throughout the period of the experiment. The difference in growth is quite conclusive evidence of the value of the dust mulch.

A number of other experiments similar to these were conducted, and it was found repeatedly that if the soil is thoroughly puddled no appreciable growth will take place if the puddled state is maintained and no cracks or other sources of air for the roots are developed.

The effect of dust mulch on the availability of plant food and its absorption by the plant was studied in the next experiment by means of the modified Neubauer test. In this experiment 100-gram portions of soil were puddled with a spatula after adding 25 cc. of water per 100 grams of soil (approximately the moisture equivalent). They were then used for the quantitative determination of plant-food absorption as follows: (1) dried for two weeks under a cover of 50 grams finely ground soil (dust mulch); (2) dried for two weeks exposed to the air (not mulched); (3) planted while wet immediately after puddling with 50 grams of dust spread over the surface of the puddled soil; (4) planted immediately after puddling but without the addition of the dry mulch. Each of these cultures contained 150 grams of soil instead of the 100 grams usually employed in the Neubauer test. Thus the experiment compared the effect of a finely ground soil mulch on the dried and undried puddled soil with the same dried and undried soils when mulched. One hundred rye seeds were planted in each culture, grown for fourteen days, and then analyzed for potassium and phosphate. These data are given in Table 1.

TABLE 1.—EFFECT OF DUST MULCH ON PLANT-FOOD ABSORPTION AS TOTAL MILLIGRAMS ABSORBED.

Plant food	Puddled, dried		Puddled, not dried		Control
	not mulched	mulched	not mulched	mulched	
Phosphate (PO_4)	29.2	30.2	29.0	30.5	32.7
Potassium (K)	28.8	34.1	29.7	33.2	36.7

It is quite evident that puddling reduces the absorption of potassium and phosphorus and that the dust mulch increases the absorption of these elements as compared with the puddled soils which were not mulched. This experiment shows that in addition to an improvement in the soil structure (22) and available nitrogen (8) a dust mulch will increase the availability of potassium and phosphorus in a puddled soil. The experiment does not, however, tell us whether this greater absorption is an actual increase in availability or is due to more extensive root foraging from the structurally improved soil. We believe that the dust mulch operates by reducing the rate of loss of water from the puddled-soil surface which it protects. That is, it acts as a blanket and thus protects the surface from the excessive temperature and humidity fluctuations so common in the Southwest. This applies especially to clays which have a greater range of structural change.

This observation is somewhat of interest in connection with the controversy over the value of cultivation. Call and Sewell (10) found that cultivation was no more effective than a bare uncultivated condition for preventing evaporation. It conserves moisture only by eliminating weeds and preventing runoff. They also found no difference in the nitrate content of the soil under the two conditions, which does not agree with our findings (8). It is significant that little attention has been given to the effect of cultivation on the structure of the soil below the cultivated depth, except the occasional reference to a plow sole, and this is an extremely important point to consider in drawing conclusions.

Our laboratory experiments have demonstrated measurable differences in the physical structure of puddled soils dried under a dust mulch and without the mulch (22). These studies have shown that without the protection of the dust mulch the soil dries into a much more compact form which on pulverizing breaks into larger lumps. After slaking the soils for twenty-four hours, a mechanical analysis, using the Bouyoucos hydrometer method and without employing any dispersing agents or mechanical dispersion, showed that the soil dried under the mulch exhibited a slower settling rate and therefore an apparent greater percentage of suspended solids (22). A determination of settling volume of the two soils also showed the same difference in aggregate structure—that is, the soil dried under the mulch showed the greatest settling volume. The crumbs were smaller but appeared to be more water stable.

Effect of Dry Fallow on Plant Growth in a Puddled Soil

Puddling does not necessarily represent permanent injury to the soil, for field experience has shown that structure can be rebuilt by dry fallowing. Then, again, our laboratory experiments have shown that the biological activities associated with nitrogen transformations in the soil are revived by drying (8).

It is our custom to recommend a thorough dry fallow for the reclamation of puddled soils. When a puddled soil dries to a hard, dense mass it will crumble to a granular crumblike condition on rewetting. The effectiveness of this reconstruction operation is aided by the use of gypsum, sulphur, manure, or similar soil amendments which should also impart greater water stability to the crumbs. The time over which this period of reconstruction should extend depends entirely upon the water stability of the crumbs, for the less-stable crumbs may soon revert to a puddled state. In this case several alternate dry and wet periods may be required.

Alternate wetting and drying is apparently a common method for reclaiming puddled soils in regions other than the arid West.

Quoting the observations of Bouyoucos (6)

> natural soils of the fine textured type, under normal conditions, nearly always possess this granular structure which is so desirable and important for the ultimate object—the successful growth of plants. In case the granular structure is destroyed, by any means, the soil soon recovers it upon being exposed to alternate wet and dry weather conditions. Among the factors which bring about a granular structure are—freezing and thawing, organic matter, lime, plant roots, animals and tillage operations.

It is claimed by some investigators that as the moisture content of the soil is reduced during the drying operation, the pulling power of the thinned water films is increased and they tend to bring or draw the soil particles together into granules. Bouyoucos claims that the facts do not support this hypothesis and states, "water brings about the formation of granular structure, not by pulling the soil particles together but by pushing them apart and thus giving rise to the crumbling of dense masses or clods into a loose and granular structure."

It is the experience of the authors that both these hypotheses may be applicable under southwestern conditions. On drying a puddled soil it dries to a compact mass, the cracking of which is governed by the lines of weakness in the adhesive forces. That is, the soil particles are drawn to closer contact as the moisture film is reduced by the drying of the soil mass. The size of the dried lumps is governed by the degree of puddling and therefore to the extent the air is able to enter the cracks or pore spaces (as the drying process proceeds) occupied by the water. On rewetting the dry soil the amount of structure that will be rebuilt will depend upon the thoroughness with which the soil has been dried. A thoroughly dried puddled soil will have the greatest amount of pore space occupied by air and will also have a greater attraction for water. Thus on rewetting such a soil, water is able to push into a greater number of pore spaces which, together with the expansion of the shrunken soil, tends to burst the larger clods into small granules. Of course in alkali soils a number of chemical factors arising from soil drying contribute to the rebuilding of small aggregates. Among these are bicarbonates and the effect of the alternate wetting and drying on the base-exchange complex. Sodium clays—that is, clays containing a certain percentage of sodium—are more difficult to reconstruct than calcium clays. This is one reason we recommend gypsum, sulphur, or manure be included in the operation of reconstruction. Russell (24) says "if more than 20-30 per cent of the exchangeable ions in a soil are sodium the soil will usually form water unstable crumbs." Therefore some form of soluble calcium must be present during the reconstruction for the conversion of the major part of this sodium clay into calcium clay.

Russell's (24) explanation of crumb structure is also of interest: "The alternate method of producing a tilth from large clods is to let them dry out and then cultivate after the first shower of rain. By cultivating under such conditions an experienced cultivator can produce a very good structure." This is in agreement with our observations that soil structure and plant growth were improved when the soil was worked with minimum amounts of water (10 cc. water per 100 grams of soil).

On wetting a fairly large dry clod the absorbed air which is liberated from the surface of the colloidal material binding the soil into the clod cannot in general escape unless it has been liberated near the outside of the clod. The air forms channels and holes in the clod so that on drying it becomes more sponge like and consequently mechanically weaker.

He states that hard crumbs can only be formed in soils of base-exchange capacity in excess of 20 milliequivalents per 100 grams.

The next experiments were designed to show the effect of drying a puddled soil on plant growth and on the absorption of plant food from the soil by the plants.

In Plate IV the effect of drying a puddled soil is illustrated by a photograph which represents one of many experiments of this type which were conducted. The soil in *1* represents the control—that is, the soil in its original state; *2* represents the growth obtained in the puddled soil, and *3* represents the growth obtained by drying the puddled soil previous to planting the seedlings. It is clearly evident from this experiment that the productivity of this soil has been restored by drying.

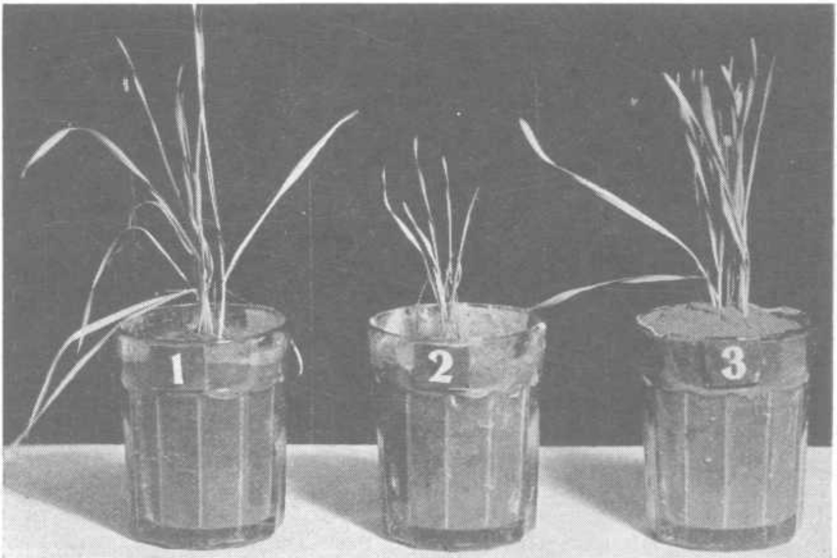

Plate IV.—The effect of drying a puddled soil on its fertility: *1*, control; *2*, soil puddled; *3*, soil puddled and dried before planting barley seedlings.

For a study of the effect of drying on the availability of plant food in a puddled soil the Neubauer test was employed. In this experiment ten 100-gram portions of soil were puddled with 25 cc. of water. They were then separated into duplicates. Two were dried for eleven days, two were dried for six days, two were dried in the electric oven at 105 degrees C., and the other two were not dried. All were then cultured by the Neubauer procedure, the dried soils being ground in a mortar before planting. The plants grown in the cultures were analyzed, and the data obtained are given in Table 2.

TABLE 2.—EFFECT OF DRYING ON AVAILABILITY OF PLANT FOOD IN PUDDLED SOIL.

	Potassium (mgm. K)	Phosphate (mgm. PO_4)	Calcium (mgm. Ca)
Control	45.5	32.0	13.1
Puddled soil dried 11 days	42.8	26.6	10.1
Puddled soil dried 6 days	43.3	28.5	7.8
Puddled soil not dried	42.8	28.4	6.8
Puddled soil dried in oven	. ..	30.0	11.2

These figures represent milligrams of potassium, phosphate, and calcium removed from 100 grams of soil by the plants grown in the cultures. Potassium is reduced by puddling, but there appears to be little or no effect on potassium absorption from the dried soils. Puddling reduced the availability of phosphate, and like the potassium there was no increase in availability from drying except where the soil was dried in the oven. Calcium availability was materially reduced by puddling and showed a notable increase in availability in the dried soils. Experiments on soil drying in Russia led Lebedjantzev (20) to state: "Drying is one of the powerful factors which help to transfer the fertility elements of the soil from a potential to an active form." The sun is truly a powerful ally of the farmer.

Vibration as a Cause of Soil Puddling

Assuming that soil productivity in irrigated regions does decline as the period of cropping is extended, and there is plenty of evidence of this, certain phases of the practice of cultivation become of paramount importance. Cultivation of the soil when bare of crops can usually be better timed to suit the moisture conditions, from which it appears that the cultivation conducted during crop growth is most often the cause of structural deterioration. In the latter type of cultivation the principal object is to control weeds and to break the surface crust of the soil, and this operation is often guided by the appearance of the surface soil with little or no consideration of the moisture conditions in the subsoil. If a light farm implement is employed there may be little or no damage. On the other hand, if a gasoline-powered implement is employed the soil will be subjected to considerable vibration from the concussion of the motor, and this vibration will extend to greater or lesser depths depending upon the weight of the implement. We suspect that much subsoil puddling arises from the concussion of power-driven farm implements. We have conducted a number of experiments to study this.

In these experiments the concussion of the gasoline motor was imitated by an electric vibrator as shown in Plate V. This vibrator has a piston a little off center which causes the contact point, a Bakelite ball, to vibrate about a millimeter backwards and forwards horizontally. If a soil is placed in a pot or tumbler, moistened with water to the point represented by the moisture equivalent, and the vibrator, while in motion, held firmly against the side or bottom of the pot, the soil will at once begin to puddle or coalesce. Air bubbles will rise from the soil, and after a few minutes the soil will decrease in volume and possess a compact structure. Some experiments were conducted in which pots of soil were treated as above after planting seeds, and in every case the seeds failed to germinate.

In other experiments wheat, barley, and tomato seedlings were germinated in sand and when about 5 inches tall were transferred to soils and the soils then puddled by vibration. The puddling treatment completely stopped growth, and after a few days all the plants wilted and died. They gave every appearance of wilting from lack of water, yet the soils were saturated.

Plate V shows two cultures of barley seedlings. These seedlings were sprouted in sand trays and when six days old transplanted to the soil. The soil was then brought to a moisture content of 33 per cent, and the jar on the right was puddled by vibration. The culture on the left acted as an unpuddled control. Both were kept at a constant moisture content by weighing daily for a period of twelve days. At this time the plants in the puddled soil were dead.

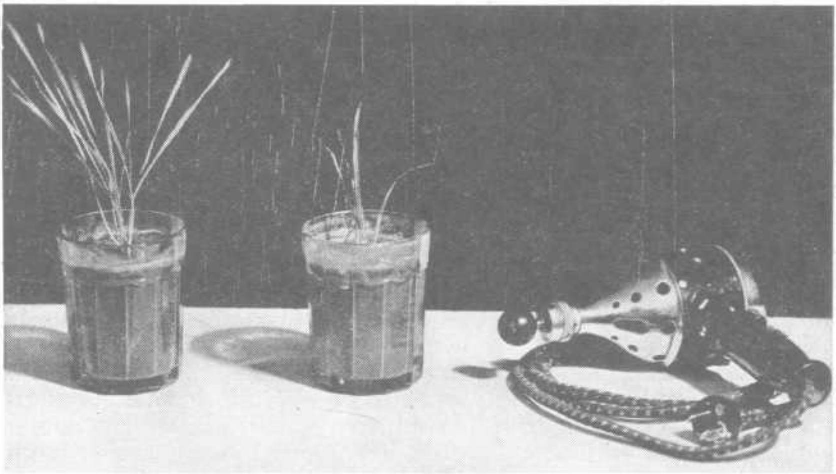

Plate V.—The effect of puddling induced by vibration on the growth of barley seedlings: left, control; right, puddled soil.

Moisture Relations in Puddled Soils

Of all the physical constants which are determined on soils, those involving the moisture relationships are most important and indicative of the true structure of the soil. Water plays a tremendously important role in producing and keeping good tilth in soils. Greene and Snow (16) state, "the physical property of the soil which seems most directly related to fertility is its capacity to store water for the use of the plant and to do this without obstructing aeration."

When a soil is vibrated, as in the preceding experiments, one of the principal conditions developed is an almost complete elimination of air from the soil with the soil mass being converted into a continuum approaching a gel. On the other hand, as already mentioned. the plants in the puddled soils give the appearance of having died for want of water. The leaves curl badly and give every evidence of the sort of moisture stress exhibited by plants growing in a soil which is near the wilting percentage. The question then arises as to the amount of bound water in puddled soils, or whether the absence of air and the physical structure of the soil reduce the availability of the water.

There are two conditions which might contribute to the behavior of the plants in the puddled soils. One of these is a restricted root system which is unable to supply the moisture requirement of the plant, and the other is the inability of the roots to extract the water from the puddled soil. Our experiments show that both these conditions contribute to the plant distress in puddled soils.

Root elongation can proceed only in the presence of an ample supply of oxygen, and roots will cease to function when oxygen reaches a certain minimum. Since there can be no soil breathing in a puddled soil, root growth will be completely stopped if a puddled condition is maintained. In Plate VI the effect of a puddled soil structure on the root growth of barley plants is illustrated. This experiment was repeated many times under a number of conditions, and root growth was never obtained in a puddled soil. In other experiments the authors have shown how plant roots will turn away from a pocket of puddled soil located in a soil of good structure (23).

The next experiments were designed to study the apparent moisture stress exhibited by the plants The results obtained from one of these experiments are shown in Plate VII. Three glass tumblers containing barley plants growing in soils were prepared. Two of these were puddled with a vibrator and the third left in its original unpuddled state. One of the puddled soil cultures was allowed to remain in the open air, while the other was placed under a bell jar. The relative growth is clearly shown in Plate VII. While the growth obtained in the plants growing under the bell jar does not equal that of the control, it is clearly evident that reducing the rate of transpiration has greatly increased growth. In the absorption of water from soil there must be a

Plate VI.—Reduction of root growth under puddled-soil conditions: left, barley plants sixteen days old grown in good soil; right, barley plants sixteen days old grown in puddled soil.

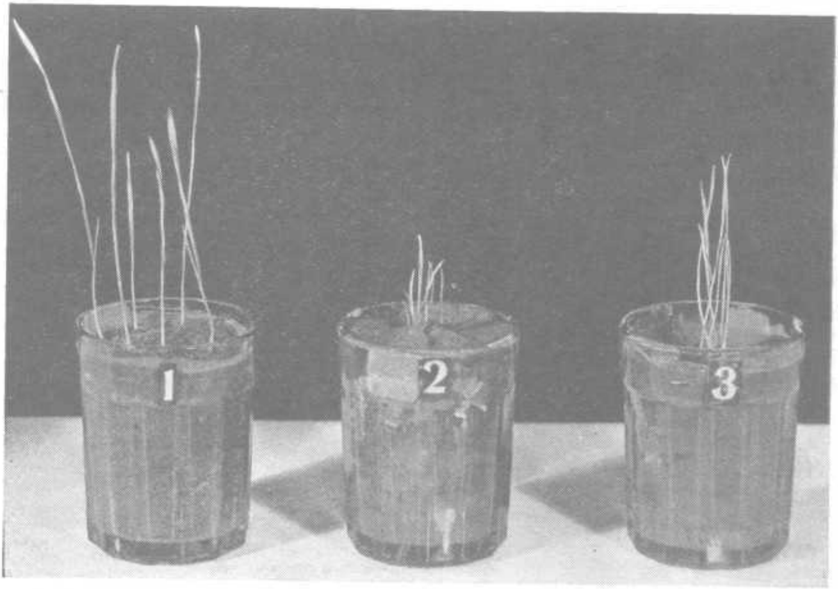

Plate VII.—Relative growth obtained in puddled soil when exposed to air and when kept under a bell jar: *1*, control; *2*, soil puddled and plants grown exposed to air; *3*, soil puddled and plants grown under a bell jar.

free movement of both water and air to refill the space or pores vacated by the soil moisture which is absorbed by the roots, otherwise the roots are soon pulling against a partial vacuum. If transpiration is too rapid the plant actually suffers for lack of water in spite of the fact that an excess is present in the soil. If transpiration is reduced, as under the bell jar, the water required by the above-ground part of the plant is reduced both in rate and in quantity, and the plant is able to adjust itself to a certain extent.

We thus have in puddled soils a moisture stress in spite of the presence of an excess of water and an air stress due to an actual deficiency. The significance of this observation will be at once apparent to everyone familiar with the growth of crops in semi-arid regions. The rate of transpiration is very high because of the high temperature and low humidity. Even in a soil of good structure many crops are under stress and must use moisture in the most efficient manner nature can devise. It is evident then that any degree of soil puddling should seriously affect growth.

Summer crops growing in heavy soils will often suffer sufficient stress during the hot days to seriously retard maturity and reduce yields. The roots, being unable to absorb sufficient moisture from the partially puddled soils, place the above-ground part of the plant under stress. With the approach of shorter days and lower temperatures during late summer the rate of transpiration is reduced, and accompanying this the moisture stress will slacken. Plant growth is stimulated but often too late for the crop to make up the lost growing time.

Further study of the nature of the moisture stress exhibited by plants growing in puddled soils was conducted by employing the phenomenon of guttation which is exhibited by plants growing under certain conditions of temperature and humidity. For example, it is well known that some plants growing in a moist soil and in a saturated atmosphere will show an accumulation of water drops on the tip ends of the leaves. This phenomenon, known as guttation, is a characteristic of grasses and cereals. The mechanism of guttation is not thoroughly understood, but it was used in this experiment to study the free movement of water in the soil for which it proved to be peculiarly adapted.

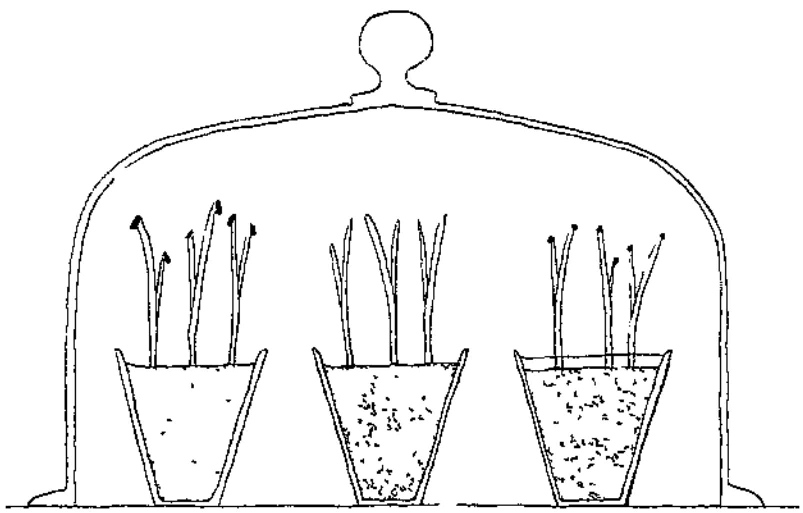

Figure 1.—The absence of guttation in plants growing in puddled soil: left, plants growing in normal soil; middle, plants growing in puddled soil; right, plants growing in puddled soil containing an excess of water on the surface.

Wheat and barley seedlings were sprouted in a heavy soil, and when the plumules were 2 to 3 inches high sufficient water was added to increase the moisture content of the soil to approximately that represented by the moisture equivalent, and the soils were then puddled by vibration. A number of control cultures—that is, plants growing in unpuddled soils—were included as a part of the experiment Some others were brought to a waterlogged condition but not puddled. All these cultures were placed under a large bell jar, the atmosphere in the bell jar being saturated with water, and were allowed to remain in this atmosphere over night. The next morning large drops of water were present on the tips of the leaves of all plants growing in the unpuddled soils, while no guttation was present on any of the plants growing in the puddled soils. In one case an excess of water was added to a puddled soil— that is, a sufficient amount to allow ¼ inch of free water on the surface of the puddled soil. These plants showed very slight guttation, and it is believed that this moisture was absorbed through the stem of the plant from the surface water and was not supplied by the roots. This experiment is illustrated in Figure 1. It shows in the one case the presence of ample free-moving water in the control and little or no available water in the puddled soil. In other words the pull of the soil for water is greater than the pull of the plant against the partial vacuum.

COMPARISON OF PUDDLED AND WATERLOGGED SOILS

Throughout our investigations on puddled soils we have continually observed notable differences in the physical properties and the nitrogen transformations taking place in puddled and waterlogged soils. Our observations indicate that while waterlogged soils possess a lower productivity rating than normal soils,

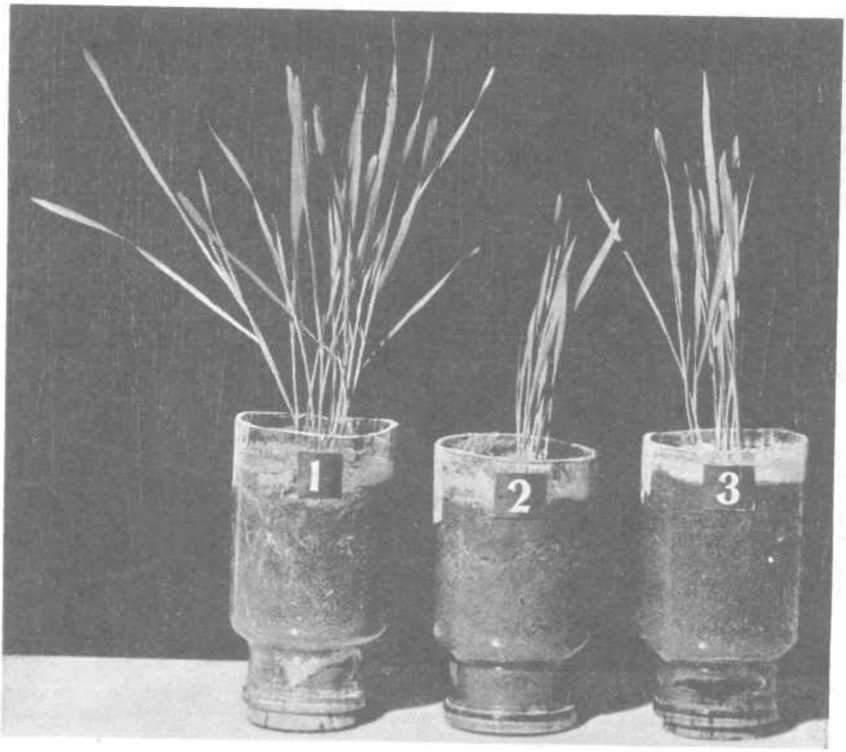

Plate VIII.—Comparison of growth in puddled and waterlogged soils: *1*, control; *2*, puddled soil; *3*, waterlogged soil.

they dc nct lose their structure as do the puddled soils. Their low productivity is merely a lack of aeration rather than a structural deterioration

In the next experiment a comparison was made among the growth of barley seedlings in normal soil, puddled soil, and soil kept saturated with water but not allowed to become stagnant. The growth obtained under these three conditions is shown in Plate VIII. This experiment shows that the continual presence of an excess of water in the root zone is not harmful as long as the water is kept moving, for such water contains considerable dissolved air. While the plants grown in the waterlogged soil are slightly smaller, this is probably due to the loss in soluble plant food in the leachate.

Decomposition of Organic Matter under Puddled Conditions

Because of the very low organic-matter content of southwestern soils, green and animal manures are extensively employed for supplying this deficiency. While it is true that organic materials may improve the fertility of the soil, regardless of the kind of organic matter or its rate of decomposition, the effect on plant growth is greatly influenced by the nature of the decomposition, and the nature of the decomposition is governed by the soil structure.

In order for a desirable decomposition of organic matter to take place in soils, an ample supply of air or oxygen must be available. Since this kind of environment is foreign to puddled soils it is considered very undesirable to incorporate organic matter with puddled soils unless the soils are thoroughly dry and in the process of structural rebuilding. Even in normal soils it is not desirable to add fresh organic material while a crop is being grown because of the toxic products of decomposition. In view of this the next experiment was designed to determine the toxicity of the organic decomposition products in puddled soils and how long the toxic condition will remain in the soil. The following is an outline of the experiment:

1. Control, soil untreated.
2. Soil to which 1.5 per cent dry alfalfa hay was added, the whole incubated for forty days at optimum moisture content, and then dried in the air before planting.
3. Soil to which 1.5 per cent dry alfalfa hay was added. The whole was then puddled, incubated for forty days, and then dried in the air before planting.
4. Soil to which 1.5 per cent alfalfa hay was added after being thoroughly rotted. This rotted alfalfa was added to the soil at planting time. This soil was not puddled.
5. Soil treated same as 4 with regard to addition of organic matter but was puddled in this case.

All these soils were planted to barley seedlings and after thirteen days were photographed as shown in Plate IX. The numbers in the illustration correspond with the numbers above.

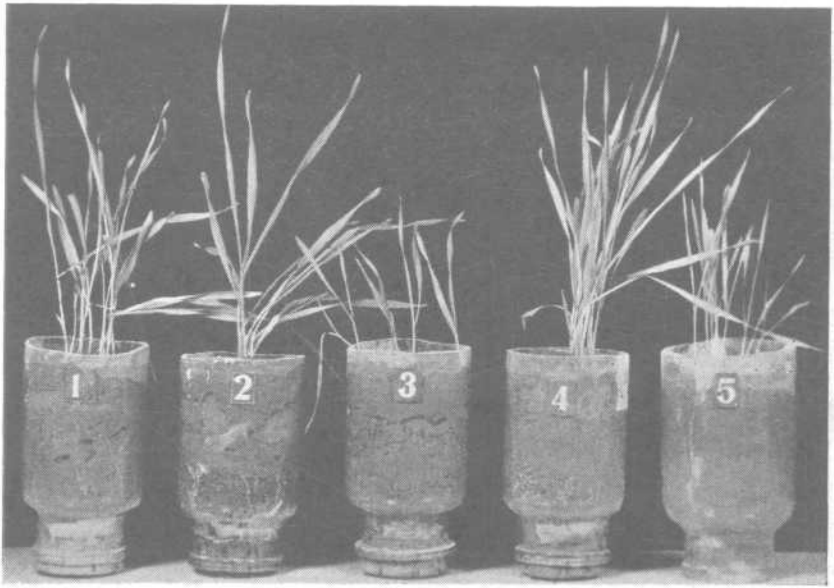

Plate IX.—The effect of organic matter decomposition in normal and puddled soils on plant growth: *1*, control; *2*, unpuddled; *3*, puddled, incubated, and dried; *4*, rotted organic matter added to unpuddled soil; *5*, rotted organic matter added to puddled soil.

In the unpuddled soils to which dry and rotted alfalfa were added excellent plant growth was obtained, and the plants appeared to be getting plenty of nitrogen. In the puddled soils the plants made very poor growth, were quite yellow, and appeared to lack both nitrogen and water. There was practically no root development in the puddled cultures (*3* and *5*). Culture *3* is of special interest. In this case the soil was given a thorough drying after the alfalfa had undergone anaerobic decomposition in the puddled soil. It is apparent, therefore, that the toxicity persisted in the soil even after a thorough drying and aeration. Following the above experiment the same soils were held for three months and again planted; the toxic condition in *3* was still present in the soil.

This experiment shows that the productivity of puddled soils may be seriously reduced by the incorporation of organic matter while the puddled condition still exists and that in utilizing organic matter in the rebuilding of soil structure productivity may be lost, even though the structure is regained, if proper precautions are not taken in the use of organic matter.

Fertilization of Puddled Soils

The influence of a puddled soil structure on the productivity of Arizona soils has been discussed in several other of our technical bulletins. Two important phases are the effect of restricted aeration on soil reaction (pH) and upon phosphate availability. Normal carbonates and hydroxides often arise in soils from a deficiency of carbon dioxide (poor aeration). Evidence of this is shown by the fact that with rare exceptions the subsoils have a higher pH than the surface soils, and the phosphate availability is also lower in the subsoil.

On this basis we should expect plant growth in puddled soils to be affected by pH value, phosphate deficiency, nitrate deficiency, and other factors aside from restricted root growth and a moisture and air stress. A number of experiments were designed to obtain some quantitative data on the effect of soil puddling on plant food availability and the efficiency of fertilizer applications.

Plate X.—The failure of puddled soils to respond to fertilization (lower row, puddled soils; upper row, not puddled): *1-2*, control; *3-4*, treble super; *5-6*, ammonium sulphate; *7-8*, sodium nitrate; *9-10*, sodium nitrate and treble super.

The first experiment shown in Plate X illustrates the manner in which plants are unable to use plant food added as fertilizer in puddled soils. Ten pots were filled with soil which was known to be deficient in phosphate and nitrogen. One set of five pots, the upper row in Plate X, was in good physical condition and was maintained so throughout the experiment. In the other series of five pots, the lower row in Plate X, the soil was worked into a puddled state. The soils were then fertilized and planted to tomatoes. Both sets were kept at approximately the same moisture content. The following fertilizers were applied:

1 and *2* control
3 and *4* treble superphosphate, 1 ton per acre
5 and *6* ammonium sulphate, 1 ton per acre
7 and *8* sodium nitrate, 1 ton per acre
9 and *10* treble super and sodium nitrate, 1 ton per acre

This experiment shows in a very convincing manner that puddling the soil will seriously reduce the efficiency of fertilizer. The puddled soils show little or no growth beyond the postgermination stage as evidenced by a comparison with the normal fertilized and unfertilized pots. Pots *6* and *8* show a slight improvement in growth as compared with *2*, *4*, and *10*, indicating that these plants were able to absorb a small amount of nitrogen. These applications were intentionally made heavy so that even with a restricted root system an ample supply of nitrogen and phosphate would be accessible to the plant.

This simple experiment contributes evidence of the waste that will follow the use of fertilizers on soils of puddled structure. Many experiments have shown that some crops give more profitable response to fertilization on good soils than on poor soils—that it, where good and poor applies to structural classification. As an example, we may cite the work of Gracie (15) and his coworkers in Egypt. Their experiments showed that cotton on irrigated lands often responds less to fertilization on low-yielding land than on high-yielding land. Apparently, however, the nature of the root system is an important factor, for they found that maize gave best response to fertilizer on the low-yielding land.

Availability of Phosphate, Potassium, and Calcium in Puddled Soils

In an attempt to obtain some quantitative figures on the availability of phosphate and nitrogen in puddled soils, we resorted to the Neubauer plant test. For this work the regular Neubauer procedure was followed with only slight modification. In all experiments controls of 100 rye seeds in sand and 100 rye seeds in unpuddled soil were included. Comparisons were based on the results obtained from these controls and the analytical data obtained from the same soil when worked with water to produce a puddled condition. The plants were analyzed for potassium, phosphate, and calcium, and the data are given in Table 3.

TABLE 3.—EFFECT OF SOIL PUDDLING ON ABSORPTION OF POTASSIUM, PHOSPHATE, AND CALCIUM IN NEUBAUER TESTS.

	Potassium (mgm. K)		Phosphate (mgm. PO_4)		Calcium (mgm. Ca)	
	a	b	a	b	a	b
1. Sand	17.7	....	27.8	...	8.5	...
2. Soil control	54.2	....	34.9	.....	9.8	...
3. Soil worked, 10 cc. water	52.8	54.2	33.6	34.0	13.2	9.1
4. Soil puddled, 25 cc. water	52.4	55.8	31.3	34.6	6.2	9.3

Reading across the table the row marked 1 represents the milligrams potassium, phosphate, and calcium obtained from the 100 plants grown in sand; row 2 represents the milligrams obtained from 100 plants grown in soil; row 3, column a, represents the milligrams obtained from 100 plants grown in soil which had been worked with 10 cc. water per 100 grams soil before planting; row 3, column b, is the same as 3,a except that the water was added to the soil in the culture dish, but the soil was not worked as in 3,a; row 4, column a, represents the milligrams obtained from 100 plants grown in soil which had been puddled at a moisture content of 25 cc. water per 100 grams of air-dry soil; row 4, column b, is the same as 3,b except that 25 cc. of water per 100 grams were added but not worked into the soil. The b columns in reality are simply additional controls and should agree with row 2. All these cultures were kept at the same moisture content during the entire period of growth. Each variation in treatment was conducted in quadruplicate and was preceded by two other similar experiments in which all treatments were conducted in duplicate, thus reducing experimental error to a minimum, so the results may therefore be considered conclusive.

Working water into the soil at the rate of 10 grams water per 100 grams of soil improves the structure (22), while 25 grams water per 100 grams soil gives the maximum puddling effect.

It is evident that there is a slight reduction in the amount of potassium absorbed by the plants in the puddled soils. With phosphate there is also a slight reduction. The calcium data show that 10 cc. of water per 100 grams soil increased the absorption of calcium, while in the puddled soil, 25 cc. water, there was a marked reduction in absorption of calcium. Since these data were checked by other experiments, they are reasonably accurate. The principal effect of producing a puddled-soil structure was therefore to reduce the absorption of calcium, potassium, and phosphate by the plants.

In interpreting these data one must bear in mind that in these Neubauer tests a layer of sand is placed on the bottom of the culture pan and the soil is placed on top of this. Above the soil is a layer of 100 grams of sand upon which the seed is planted and then covered by another 100 or 150 grams of sand. Thus there are plenty of pores in the sand for aeration of the roots, and the plants are not really growing in the puddled soil. They are, however, dependent upon the mass of soil for all potash, phosphate, and calcium which are absorbed beyond that which is present originally in the seed. There is unquestionably some diffusion of these elements from the soil into the surrounding solution held by the sand, and there is also some absorption from contact of the roots with the outside surface of the puddled mass.

Lipman and Blair (19) found that within certain limits the dilution of a heavy loam with sand gives a consistent increase in crop yield due to superior aeration. Undoubtedly the plant growth in the Neubauer tests was favored by the presence of the sand, and without the aeration furnished by the sand the absorption of plant food would be materially reduced below the results obtained by the authors. It is of interest that sand is sometimes used for dilution of heavy soils in Arizona.

Availability of Nitrogen in Puddled Soils

For determing the effect of puddling on the availability of nitrogen and its absorption by plants the modified Neubauer method was again employed according to the procedure already described. Four series of cultures were grown: in sand, in soil as control, in soil puddled after adding 25 cc. of water, and in soil dispersed after adding 40 cc. of water. The former is about the moisture equivalent and the latter slightly above maximum water-holding capacity. The treatments in each series included the controls to which no nitrogen was added and cultures to which calcium nitrate, ammonium sulphate, and sodium nitrate were added. All salts were added to the soil in solution and were worked into the soil during the puddling treatment. One hundred grams of soil and 100 rye seeds were used in each culture and the plants harvested and analyzed after a growth period of fifteen days. Nitrogen content of the plants was determined by the Kjeldahl method. The data obtained are given in Table 4.

TABLE 4.—EFFECT OF PUDDLING ON NITROGEN ABSORPTION (MGM. NITROGEN).

	No nitrogen added	Calcium nitrate	Ammonium sulphate	Sodium nitrate
Sand	39.6	64.6	66.6	65.0
Soil, control	53.6	63.1	71.4	66.5
Soil puddled, 25 cc. water	49.1	64.5	66.2	64.0
Soil worked, 40 cc. water	52.2	69.1	74.0	66.8

All nitrogen salts were added in amounts to supply 50 milligrams of nitrogen to each culture. The soils worked with 25 cc. of water were in a thoroughly puddled state, and it is quite evident that the amount of nitrogen absorbed by the plants in these puddled soils was reduced by the puddled condition and that this was not true for the plants grown in the soils worked with 40 cc. of water. This latter moisture content was sufficiently high to prevent soil puddling and was included as a part of the experiment to represent a waterlogged condition.

Availability of Phosphate in Puddled Soils

Neubauer tests showing the effect of soil puddling on the absorption of phosphate by plants have already been presented. The following experiment was conducted to determine phosphate absorption when the phosphate supply in the soil is supplemented by fertilization. As in the previous experiments in which the Neubauer method was employed, controls were grown in both sand and unpuddled soil. The soils were worked at three moisture contents—namely, 10 cc., 25 cc., and 40 cc. water per 100 grams of soil. Phosphate applications were made at each of these moisture contents and added to the soil in solution previous to the working of the soils into a puddled or other state. Twenty milligrams of phosphate (PO_4) were added to each fertilized culture. The plants were grown for fourteen days, at the end of which time they were harvested and analyzed. Calcium and potassium were determined in addition to the phosphate. The data obtained are given in Table 5 and are expressed as milligrams per culture.

TABLE 5.—EFFECT OF PUDDLING UPON ABSORPTION OF PHOSPHATE.

	Control	Acid treble super	Ammonium phos.	Treble super
Milligrams calcium (Ca) absorbed per culture				
Sand	9	8.9	7.7	10.8
Soil, control	.....	10.8	11.5	10.2
Soil, worked with 10 cc. water		11.9	9.4	10.5
Soil, puddled with 25 cc. water	. .	8.7	7.5	9.0
Soil, worked with 40 cc. water	......	9.0	8.5	8.7
Milligrams phosphate (PO_4) absorbed per culture				
Sand	27.0	37.9	36.6	38.6
Soil, control	30.6	38.1	37.1	38.5
Soil, worked with 10 cc. water	......	38.2	37.9	37.3
Soil, puddled with 25 cc. water	....	34.0	37.1	35.0
Soil, worked with 40 cc. water	......	36.5	39.1	28.7
Milligrams potassium (K) absorbed per culture				
Sand	12.2	12.2	23.0	15.7
Soil, control	29.1	29.6	49.2	32.6
Soil, worked with 10 cc. water	. ...	33.3	49.2	32.8
Soil, puddled with 25 cc. water	.... .	29.1	44.8	30.8
Soil, worked with 40 cc. water	......	28.7	47.0	30.0

This experiment shows that about 8 milligrams, of the 20 milligrams added, were absorbed by the plants in the untreated soils. This absorption was not affected by working the soils with 10 cc. of water but was materially reduced when the soil was puddled by working with 25 cc. of water. The calcium and potassium determinations were made on this series of cultures as a supplement to the other experiments. Both calcium and potassium absorption were materially less in the plants grown in the puddled soils.

AVAILABILITY OF CALCIUM IN PUDDLED SOILS

In view of the evidence obtained in all the Neubauer cultures showing a material reduction in the absorption of calcium by the plant in puddled soils, a separate experiment was conducted to determine the effect of puddling on the absorption of this element. The experimental procedure was the same as that described in the previous experiment except that 16 milligrams of calcium from gypsum, calcium nitrate, and calcium sulphate were added per 100 grams of soil.

TABLE 6.—EFFECT OF SOIL PUDDLING ON ABSORPTION OF CALCIUM FROM CALCIUM SULPHATE, NITRATE, AND CHLORIDE.

	Control	Calcium sulphate	Calcium nitrate	Calcium chloride
Milligrams calcium (Ca) absorbed per culture				
Sand	10.7	14.7	12.0	12.2
Soil, control	......	15.5	13.5	13.0
Soil, puddled with 25 cc. water	......	9.5	9.0	10.2
Soil, worked with 40 cc. water	......	10.0	10.0	10.0
Milligrams phosphate (PO_4) absorbed per culture				
Sand	27.5	27.5	26.6	30.8
Soil, control	33.5	32.1	33.6	31.3
Soil, puddled with 25 cc. water	......	28.6	30.4	29.4
Soil, worked with 40 cc. water	......	31.8	31.1	31.6
Milligrams potassium (K) absorbed per culture				
Sand	19.7	20.5	18.3	18.4
Soil, control	52.4	52.4	52.4	45.9
Soil, puddled with 25 cc. water	......	47.1	50.3	43.7
Soil, worked with 40 cc. water	......	48.1	44.8	44.8

The analyses of the plants are given in Table 6 and include the phosphate and potassium as well as the calcium, and all are expressed as milligrams per culture.

This experiment shows quite conclusively that a puddled soil condition reduces the absorption of calcium by the plants even when that present in the soil is supplemented by the addition of a soluble calcium salt. It also shows that absorption in a puddled soil is definitely less than in a waterlogged soil. The data on phosphate and potassium give additional proof of reduced absorption of these elements in puddled soils.

SUMMARY

In all investigations on soil productivity one must ultimately resort to plant behavior, for the final answer always lies with the plant. The investigations presented in this bulletin, which is the fourth of a series on soil structure, deal with the effect of a puddled-soil structure on plant growth in its several phases.

Poor growth of crops on puddled soils is the resultant of several major factors and many minor or indirect influences. The major

factors are restricted water and air movement in the soil, restricted oxygen and carbon-dioxide exchange or oxygen-carbon dioxide balance in the soil air and soil solution, and reduced absorption of plant food by the crop. We recognize that root activity is influenced fully as much by soil air as by water and nutrients. Associated with these soil conditions there are certain plant characters such as the absence of root hairs, toxicity of carbon dioxide (lack of oxygen), and a reduced root system. All these conditions are characteristic of both waterlogged and puddled soils, but the latter possess an additional property of structural breakdown which does not necessarily exist in the former.

Throughout our investigations on puddled soils we have used the word "continuum" in describing the puddled state. This term is suggested as one which best expresses the arrangement of the clay particles in a puddled state as differentiated from that in a dispersed state.

The colloidal behavior of soil particles becomes more pronounced as the size decreases and usually starts with the silt fraction. While some of the large soil particles are near-spherical, most evidence indicates that the clay particles are platelike. When soils are dispersed in an excess of water the films exert a dominant influence. At lower moisture contents, for example the moisture equivalent, the solid clay dominates. In the former the clay particles are held apart by the thickness of the water film. In the latter the platelike particles, on working, cleave along their cleavage planes, thus forming a continuum. These characters are illustrated in Figure 2 and are based upon similar illustrations given by Baver (4) and Kubiena (18). In this figure, *A* and *B* are taken from Kubiena, *A* representing a puddled mass of soil and *B* representing crumb aggregate. *A* is practically devoid of air, while *B* is open and porous. When a root attempts to penetrate the *A* type of structure, being unable to withdraw water or plant food and to exchange its carbon dioxide for oxygen, elongation ceases. In the *B* type of structure root elongation proceeds unrestricted. The reaction of roots toward the two types of structure is shown in the illustration.

Assuming a platelike character for clay particles, their arrangement in two types of soil structure is illustrated by *C* and *D*. These illustrations are based on those of Baver (4).

These illustrations are presented in order to show the difference between a crumb structure, a dispersed state, and a puddled state. In the crumb structure the clay particles are drawn together in aggregates. In the dispersed state the clay particles are held apart by the thickness of the moisture films which dominate the structure. While not puddled the particles exist as individuals rather than aggregates. The difference between the dispersed state and the puddled state is illustrated by *D*, in which the platelike particles are packed together along their cleavage planes. This type of compaction does not necessarily exist in dispersed

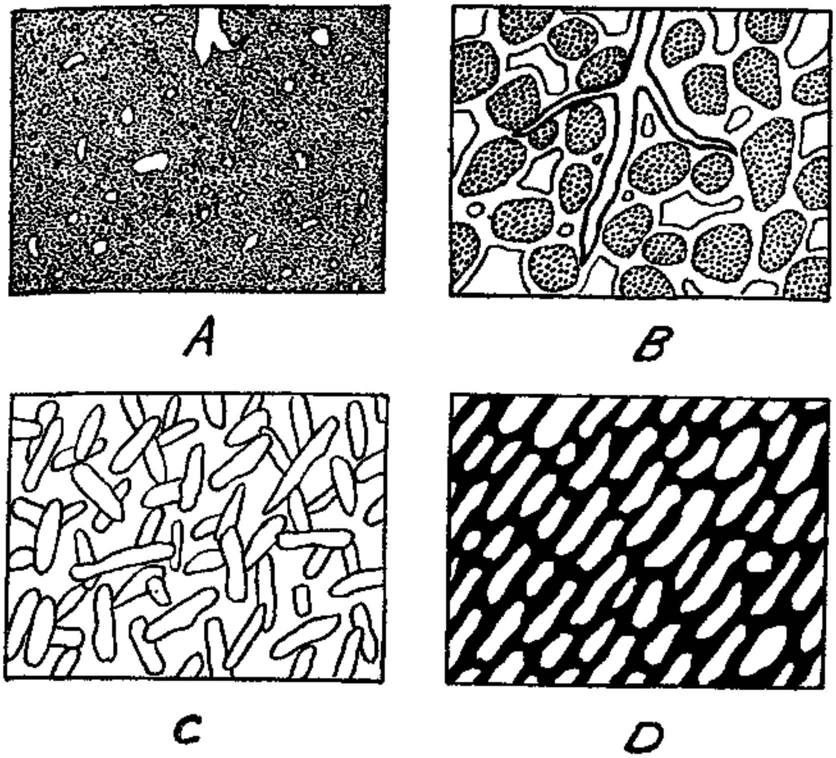

Figure 2.—The arrangement of clay particles as aggregates in a dispersed state and in a puddled state.

soils. The relative growth of roots in these several soil structures can be readily visualized from a study of these illustrations.

The plant root draws water from the film around the conglomerate and not from the film around the colloidal particles which make up the conglomerate. The conglomerate film would, at optimum moisture content or above wilting point, be over 100 molecules thick and the pull of the soil would be less than 8 atmospheres. The plant would be able to draw water under such conditions. If the film around the collōid should be less than 100 molecules thick the pull of the soil will be greater than that of the plant. Hence, when the clay particles exist as a continuum, there being no aggregates, the pull of the roots is entirely against the colloid and the plant will more easily suffer a moisture stress. By actual quantitative measurement we reduced the rate of transpiration by 50 per cent when the soil in the plant cultures was puddled by vibration.

The soils of the irrigated valleys of Arizona which are subject to puddling are clay loam and closely related types. They are highly calcareous, contain widely varying amounts of soluble salts, and have *p*H values which are usually within the range of 8.0 to 9.0.[1] Our experiments show that once these soils become puddled they adversely affect both seed germination and plant growth, and that little or no stimulation in plant growth on such soils can be obtained by fertilization unless the puddled structure is replaced by one possessing crumb aggregates which will correct restricted root growth, water movement, and aeration.

This is in agreement with the generally known behavior of plants grown in waterlogged soils and unaerated cultures. Loehwing (21) has shown that roots in anaerobic soils are characteristically devoid of root hairs, and thus the absorbing surface of the roots is reduced manyfold. He demonstrated experimentally that aerated roots absorb, transport, and utilize mineral nutrients more rapidly and efficiently than unaerated controls. The aerated plants absorbed more nitrogen, calcium, potassium, and phosphate and thereby the plants inaugurated reproduction earlier and maintained it longer than unaerated controls. It is also significant that he obtained more abundant nodules on soybean roots which were aerated. Dean (14) found that the aeration of roots is needed for proper root respiration, root elongation, development of root hairs, and in fact the anatomy of the whole root system. He found that well-aerated roots become decidely woody while unaerated roots remain succulent. Even surface roots in unaerated clay soil were devoid of root hairs and branches which were abundant when the clay soil was aerated. Weaver and Hummel (27) describe the discoloration of plants grown in soils deficient in air. The exclusion of oxygen from roots interferes with the respiration, the cells die, and the roots therefore cease to function as absorbers. The plants turn yellow, wilt, and will ultimately die. In a study of the effect of aeration on growth of barley Allison (2) grew plants in soil at 90 per cent saturation and at 60 per cent saturation with and without aeration. The poorest yield was obtained with the highest moisture without aeration, good yields were obtained however if the water was kept moving. Best growth was obtained with aeration, and the plant response to aeration under waterlogged conditions was decidely positive. Albert and Armstrong (1) found that an increased percentage of fruit-bud shedding and retardation in plant growth (cotton) was associated with poor soil aeration induced by maintenance of high soil moisture. The production of fruit buds was greater and per cent shedding less in the check plats than the waterlogged plats. The per cent carbon dioxide in the soil air of the unaerated plats was found to be two to three times that in the check. Similar observations have been made by Balls

[1] All the experiments presented in this bulletin were conducted on a Gila Clay loam soil which we obtained from the Tucson City farm. It is the same as the soil designated as No. 2 in *Tech. Bull.* 67.

(3) where increased shedding of cotton was caused by a rising water table. According to Bergman (5) roots will function properly under submergence as long as aeration is continued. When aeration is discontinued, carbon dioxide increases in the water, oxygen decreases, transpiration is reduced, the leaves turn yellow and finally shed. Knight (17) artifically aerated tomatoes in a heavy soil by means of underground pipes. He obtained a 10 per cent increase in yield, earlier ripening, and higher proportion of first-grade fruit. He states that 0.5 per cent carbon dioxide per liter in culture solution is sufficient to kill growing crops.

Some exerpts from the publications of Clements (13) are also of interest. Carbon dioxide in the root film is toxic if no allowance is made for its diffusion, for roots must absorb oxygen in producing carbon dioxide. Root-hair formation is suppressed by lack of oxygen. The slower water penetrates the soil, the less air it will carry into the subsoil. Aeration increases root pressure. Cannon (12) found that when oxygen was entirely removed from the soil in which roots were growing, growth ceased in all species. It is of interest that he presents data from the work of Whipple and Parker that at 20 degrees C. 1 liter of water will absorb 28 cc. of oxygen, 14 cc. of nitrogen, and 901 cc. of carbon dioxide.

Some practical suggestions on the handling of Arizona soils have recently been published by Wood (28). Since his observations are in close agreement with the results obtained in our investigations we quote from him as follows:

> If worked too soon following an irrigation, heavy soils will puddle. It is impossible to make a good seed bed for from one to three years after a puddled condition has resulted from working heavy soils when they are too wet. One of the best methods for handling such puddled soils is to plow deeply and let the field dry until it is slacked.

He advises a careful examination of the soil before plowing.

> If the dirt does not crumble readily when rubbed, after compacting in the hand, the soil is too wet to disk. If it does crumble readily upon rubbing after being compacted it should work into a good seed bed. Plowing moist soils is preferable to plowing dry and is less expensive both in power and wear and tear on tools. The land is left in better condition for future operations and air slacks the ground more readily.

These practical hints on cultivations which are based on the experience of many years of close observation on the tillage of Arizona soils bring out two points which deserve special comment. These are the observation that the soil structure is improved by plowing soils when slightly moist and injured when plowed within the range of soil compaction. Our laboratory studies have shown that the aggregation of soil particles is increased when the soil is worked at a moisture content which only moistens the soil but that the soil structure is progressively broken down as the moisture content increases beyond this and reaches a maximum at the moisture equivalent.

Our investigations present a study of two sources of puddling danger—namely, actual working of the soil when too wet and the vibration of heavy farm machinery. So far as we know this latter cause of puddling has not been mentioned in the literature on puddled soils, but it is our belief that it is a serious factor in soil compaction in the subsoil horizons on irrigated lands. Surface soils in arid districts dry out at a vastly greater rate than the subsoils, and therefore unless one examines the subsoil closely heavy cultivating implements will be brought onto the land at times when the subsoil is readily susceptible to puddling. In fact this is one of the principal hazards in the culture of arid soils. There is less uniformity of moisture than in the soils of humid climates. Often the surface 2 inches may be dry and yet at a depth of 12 or 18 inches the soil will be at its water-holding capacity.

As for rebuilding the structure of puddled soils, this may be accomplished by either a dust mulch or dry fallow. The former has only limited application, but the latter is almost universally applicable and entirely practicable It does, however, entail an extended period of idleness for the land.

A new method for studying the moisture stress in puddled soils is presented by utilizing the phenomenon of guttation. By employing this behavior of plants in a saturated atmosphere convincing evidence was obtained showing that the principal stress placed on plants growing in puddled soils is the failure of the roots to supply the moisture needed for transpiration. This condition arises because neither air nor water can move rapidly enough in puddled soils to refill the pores in the immediate vicinity of the roots at the same rate that the moisture is removed by transpiration. It was experimentally demonstrated that a reduction in rate of transpiration markedly improved the growth of plants on puddled soils. It was also shown that the magnitude of moisture stress is the principal difference between puddled and waterlogged soils. In the former it is a major factor, while under waterlogged conditions it is a minor one for normal growth can be obtained in waterlogged soils if their structure is not puddled in addition to the waterlogged condition, and provided the excess water is not stagnant.

One important phase of our investigations which deserves special emphasis is that showing the more or less permanent toxicity developed in soils when organic matter is allowed to decompose in soils that are in a puddled condition. In the use of either green manures or animal manures one should make sure the physical condition of the soil is such as to provide sufficient air for the aerobic decomposition of the material.

The effect of puddled soils on the absorption of plant food by crops and the efficiency of fertilizer applications is of paramount interest. By means of pot experiments and the use of the Neubauer test it was possible for us to demonstrate conclusively that the absorption of nitrogen, potassium, phosphate, and calcium are reduced when plants are grown on puddled soils and that if attempts are made to improve the productivity of puddled soil by the application of commercial fertilizers little or no success will result unless the structure is rebuilt. The experiments, however, did show that one of the effects of a dust mulch and dry fallow was to increase the availability of plant food in the soil.

CONCLUSIONS

1. Seed will not germinate in a puddled soil unless it is located near a soil crack or other surface where it can obtain air

2. The structure of a puddled soil will be improved by applying a dust mulch to the wet puddled soil, and accompanying this there will be an improvement in plant growth and absorption of plant food by plants grown thereon.

3. The structure of a puddled soil can be rebuilt by a dry fallow, and productivity will be restored by this procedure.

4. Soil structure may be seriously injured by the vibration of heavy farm implements.

5. One of the principal effects of a puddled state is a reduction in the availability of soil moisture. The availability of moisture in puddled soils is much lower than in waterlogged soils.

6. When organic matter is allowed to decompose in puddled soils, toxic substances will be formed which may seriously reduce their productivity, and even after the structure has been rebuilt by a dry fallow the toxic condition will still exist.

7. The availability of phosphate, potassium, calcium, and nitrogen is materially reduced by soil puddling. This is true of these elements naturally present in the soil as well as those added as commercial fertilizer.

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